Influence of Luminance Change in Subpixels on the Occurrence of Flicker Investigated by Alternating Display of Colors on a Liquid Crystal Display

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When two different colors are alternately displayed at a high speed, a mixed color is perceived. When two images of different colors are alternately displayed on a Liquid Crystal Display (LCD), a deterrent effect on copy is expected because the color of the copied image is different from that of the perceived image. It is also expected that display color increases without improvement to the LCD. However, flicker may occur in the LCD. The purpose of this study was to clarify the conditions for flickerless alternating display. We focused on subpixels constituting pixels on the LCD, and carried out three experiments. First, we examined whether flicker was felt when the light of the subpixel was blinking, and clarified the luminance range within which flickerless blinking is possible. Second, the presence or absence of flicker was examined when two colors with the same luminance were alternately displayed. Then, the range of luminance change in subpixels in an alternating display was compared with the luminance range clarified in the first step. Third, the presence or absence of flicker and the range of luminance change on subpixels were also investigated when achromatic colors were alternately displayed. The experimental results showed that the luminance change in each subpixel was related to the occurrence of flicker.

Key Words : Switching of colors, Flicker, Liquid crystal display, Subpixels, Visual characteristic

1 INTRODUCTION

When two different colors are alternately displayed at a high speed, it becomes impossible for a human to distinguish the two colors, and a mixed color is perceived [1][2]. In the application of this visual characteristic, it has been reported that the image of the original color is perceived when the images of the changed color are alternately displayed on a cathode ray tube (CRT) [3]. Since images copied by computer operations would have different colors, a deterrent effect on copying a digital image is expected. Display color is also expected to increase without physical improvement to a computer monitor that has a few display colors.

However, flicker may occur by the alternating display of colors on a Liquid Crystal Display (LCD) because the response speed of an LCD is slower than that of a CRT. This flicker must be reduced.

Flicker occurs when light is repeatedly turned on and off [1]. The flicker can be reduced by controlling the blinking extent and the repeating speed (the switching speed of colors).

We already examined the relation between the switching speed and the flicker using LCDs with a refresh rate of 60 Hz and 75 Hz. Experiments have clarified that flicker is reduced by using a switching speed of 61 fps and 75 fps, respectively [4]. There is a time lag from when the command is given until the process to change the images is executed. Therefore, it is necessary to use a switching speed that is slightly faster than the refresh rate for

synchronization with the refresh rate. By testing the switching speed in steps of 1 fps, we found that a switching speed of 61 fps was most suitable for a refresh rate of 60 Hz. However, we have not yet been able to clarify the effect of blinking extent on flicker reduction. Furthermore, to the best of our knowledge, no studies have clarified the conditions under which flicker does not occur, from the viewpoint of alternating display of images on an LCD.

Pixels in LCDs consist of a combination of three types of subpixels, namely, red, green, and blue. These subpixels emit light at intensities that respond to the RGB values in order to display colors [5]. Therefore, the luminance of each subpixel changes when the color is switched, and flicker may occur when the luminance change is large.

The purpose of this paper is to clarify the conditions for the alternating display under which flicker does not occur. First, test subjects evaluated whether they experienced flicker during blinking of subpixels, and the results clarified the luminance range in which flickerless blinking is possible. Second, the presence or absence of flicker was examined when two colors with the same luminance were alternately displayed. The colors were primary colors of the RGB colorimetric system and complementary colors. Then, range of luminance change for all subpixels in the alternating display was compared with the luminance range clarified in the first step. Third, the presence or absence of flicker and the luminance change on subpixels were also investigated when achromatic colors were

displayed alternately.

This paper is organized as follows. The background and purpose of this study was described in Section 1. Section 2 provides an experimental method for investigating whether flicker occurred when the luminance value on each subpixel was switched, and describes the experimental result. Section 3 provides a method and results of the experiment for investigating flicker when switching two different colors with the same luminance. Section 4 provides a method and results of the experiment for investigating flicker when switching achromatic colors. In Section 5, the results of this study and future work are described.

2 INVESTIGATION OF FLICKER BY LUMINANCE CHANGE ON SUBPIXELS

2.1 Display used

The specifications of the LCD (Epson LD1952G) used in the experiment are listed in Table 1. Figure 1 shows the gradation and luminance characteristics of this LCD. The data for Figure 1 were obtained from luminance of colors displayed on the entire LCD screen placed in a dark room measured using a luminance meter (Konica Minolta LS-110); the measurements were repeated ten times for each color and the average values were used. A total of 51 colors (17 gradations $\times$ 3 types) were used for the measurements by using red, green, and blue, which were changed in increments of 16 steps in the gradation value range from 0 to 255.

The luminance values and the gradation values of colors used in the experiment were converted on the basis of Figure 1. For example, in case of conversion of green at 40 cd/m^2 , the green curve was used. The dotted line shows that the gradation value equivalent to 40 cd/m^2 is 130.

In the used LCD, the output luminance level was not displayed on the screen. Therefore, this level was set to the maximum in order to ensure reproducibility of the experiment. Under this setting, at gradation values higher than 191, the luminance was

Table 1 Specifications of the LCD

Size	19.0 inches
Panel system	Color TFT
Pixel pitch	0.294 mm $\times$ 0.294 mm
Max. resolution	SXGA: 1280 $\times$ 1024
Max. number of display colors	Approx. 16.77 million colors
Max. luminance	250 cd/m^2
Contrast ratio	700:1
Response speed	25 ms
Refresh rate	60 Hz

Figure 1 Luminance and gradation characteristics of the LCD

constant, as shown in Figure 1. Therefore, the gradation values of colors used in the experiment were selected from within the range of 0 to 191.

2.2 Experimental method

Figure 2 shows an outline of the experimental conditions. The LCD was placed in an ordinary room in which a general white color fluorescent lamp was turned on. However, a fluorescent lamp directly above the LCD was turned off in order to eliminate the impact of blinking from the fluorescent lamps. The LCD screen illumination was about 250 lx. Test subjects were asked whether they could observe flicker in images displayed on the LCD.

The purpose of this experiment is to clarify the luminance range in which flicker is not observed when the light of the subpixel is blinking. Red, green, and blue images were used for blinking of the subpixels. Table 2 lists details of the first colors used for the alternating display (referred to as "used color 1"). The red and green luminance levels are incremented in 10 cd/m^2 steps, and the blue luminance level is incremented in 2.5 cd/m^2 steps. Different colors of the luminance level were prepared in order to investigate the relation between the luminance level and the flickerless luminance range. The second colors used in the alternating display were those with luminance value different from that of the first color (referred to as "used color 2"). The methods to change the luminance value were as follows:

- Change method 1: The gradation value is increased from 0 (minimum luminance value) to 191 (maximum luminance value) with increments of one.
- Change method 2: The gradation value is decreased from 191 (maximum luminance value) to 0 (minimum luminance value) with decrements of one.

Figure 3 shows an example of the combination of used color 1 and used color 2. The colors were switched at a speed of 61 fps based on previous results, for synchronization with the refresh rate of the LCD.

The judgment standard of flicker was as follows:

- "There is a flicker": When the image at the alternating display looks the same as the static image.
- "There is no flicker": All other cases.

The test subjects were 16 healthy individuals (thirteen males and three females in their twenties, all Mongoloids). They observed the alternating display until they determined the presence or absence of flicker. They looked away from the LCD screen for more than 30 seconds after each decision. In addition, in order to gain an understanding of the adverse effects on the body, such as headache

Figure 2 Outline of the experimental conditions

Table 2 Values of RGB in the first colors used for blinking on subpixel (used color 1)

Luminance [cd/m^2]	Red	Green	Blue
0.0	(110, 0, 0)	(0, 10, 0)	(0, 0, 110)
2.5	—	—	(0, 0, 196)
5.0	—	—	(0, 0, 124)
7.5	—	—	(0, 0, 146)
10.0	(116, 0, 0)	(0, 177, 0)	(0, 0, 163)
20.0	(148, 0, 0)	(0, 100, 0)	—
30.0	(172, 0, 0)	(0, 117, 0)	—
40.0	—	(0, 130, 0)	—
50.0	—	(0, 142, 0)	—
60.0	—	(0, 152, 0)	—
70.0	—	(0, 161, 0)	—
80.0	—	(0, 171, 0)	—
90.0	—	(0, 180, 0)	—

Figure 3 Combination method of used colors for blinking on subpixel (numbers in the parentheses are RGB values)

or dizziness, a simulator sickness questionnaire (SSQ) [6][7] was used before and after the experiment.

An application was filed for an ethical review based on Section 2 under Article 6 of the Ethics Standards Pertaining to Research Intended for Humans in the Tegata District of Akita University. Data collections were conducted in accordance with the approved study plan.

2.3 Experimental results

Figure 4 shows an example of the experimental result when used color 1 of green at 40 cd/m^2 (gradation value of 130) and used color 2 of green with the gradation value from 0 to 191 were used. The horizontal axis indicates the types of test subjects and the vertical axis indicates the gradation values. The solid black horizontal line indicates the gradation value for used color 1.

The red and blue lines indicate the range of the gradation values for used color 2 when the test subjects did not observe flicker. No significant differences were confirmed by using two methods for changing the gradation value of used color 2. A range shown by vertical lines of more than 16 was defined as the gradation range within which flickerless blinking is possible. The two dotted lines in Figure 4 indicate the upper limit and the lower limit of the flickerless gradation range. Gradation values were converted to luminance values. The upper limit and the lower limit were determined by the value for which half or more test subjects answered, "there is no flicker."

Figure 5 shows the result for the upper and lower limit values arranged according to the type of subpixels with the exclusion of

Figure 4 Gradation values of the used color 2 where flickerless blinking is possible for green color at 40 cd/m^2 (gradation value of 130; the upper and lower limits were decided by the value for which half or more test subjects answered, "there is no flicker")

used color 1 at 0.0 cd/m^2 . The flickerless luminance value of used color 2 is clearly in the range of about $\pm 5.5 \text{ cd/m}^2$ for the red and green subpixels, and about $\pm 2.5 \text{ cd/m}^2$ for the blue subpixel. On the other hand, when luminance value for used color 1 was 0.0 cd/m^2 , the flickerless luminance range for used color 2 is clearly within the range of about $+12.1 \text{ cd/m}^2$ for red subpixels, about $+21.0 \text{ cd/m}^2$ for green subpixels, and within the range of about $+5.5 \text{ cd/m}^2$ for blue subpixels. This experimental result indicates that the occurrence of flicker depends on the extent of the luminance change in subpixels.

It is considered that the flickerless luminance range corresponding to used color 1 at 0.0 cd/m^2 is wide because response speed is fast when the gradation value is extremely low or high. In addition, the flickerless luminance range for the blue subpixel is observed to be smaller than that for the red and green subpixels because the maximum output luminance for the blue subpixel is lower than that for the red and green subpixels. However, the above luminance ranges are values specific to the LCD used in this study. It is necessary to improve the versatility of the flickerless luminance range, which will be done in the future.

Furthermore, the results of the survey, pertaining to changes in physical conditions, which was conducted before and after the experiment confirmed that regardless of gender, there were no adverse effects on the body, such as headache or dizziness. Similar results were also obtained in subsequent experiments (see Sections 3.2 and 4.2).

3 INVESTIGATION OF FLICKER BY SWITCHING COLORS OF SAME LUMINANCE

Flicker usually occurs when colors of different luminance are switched. In this Section, to clarify the fact that the luminance change in subpixels results flicker, we evaluate the presence or absence of flicker when colors of the same luminance are displayed alternately.

3.1 Experimental method

3.1.1 Colors used

Table 3 shows colors used in the alternating display. Red, green, and blue are primary colors of the RGB colorimetric system, and yellow, cyan, and magenta are the complementary colors. Luminance values of these colors differ by 10 cd/m^2 . That is, three red, nine green, one blue, eleven yellow, eleven cyan, and five magenta are prepared (40 colors in total). The difference in the

(a) Red subpixels

(b) Green subpixels

(c) Blue subpixels

Figure 5 Luminance range of each of the subpixels for which flickerless blinking is possible

number of colors in each group (hue) is attributed to the maximum output luminance of the subpixels. Gradation values (RGB values) of complementary colors were determined based on the gradation values of the primary colors. For example, the gradation value of

Table 3 Colors for the alternating display of two different colors with the same luminance values

Luminance [cd/m^2]	Gradation value					
	R	G	B	Y	C	M
10	116	77	163	68	69	101
20	148	100	—	88	91	130
30	172	117	—	104	108	151
40	—	130	—	115	121	170
50	—	142	—	126	132	185
60	—	152	—	134	142	—
70	—	161	—	143	152	—
80	—	171	—	151	160	—
90	—	180	—	158	169	—
100	—	—	—	163	178	—
110	—	—	—	170	185	—

R: Red, (n, 0, 0). G: Green, (0, n, 0). B: Blue, (0, 0, n). Y: Yellow, (n, n, 0). C: Cyan, (0, n, n). M: Magenta, (n, 0, n). n: Gradation value.

yellow at 10 cd/m^2 was set to 68 (RGB values: (68, 68, 0)), because the sum of the luminance values of red and green at this gradation value was 10 cd/m^2 .

Two colors with the same luminance value were combined from the 40 colors shown in Table 3. For example, red at 10 cd/m^2 was combined with green, blue, yellow, cyan, and magenta, each at 10 cd/m^2 . The total number of combinations formed 61 sets.

3.1.2 Investigation of flicker

The colors of each set were displayed alternately, and the occurrence of flicker was evaluated. The test subjects, the judgment standards, and experimental conditions were the same as those described in Section 2.2.

3.1.3 Range of luminance change in subpixels

The range of luminance change on all the subpixels in the alternating display were compared with the luminance range clarified in Section 2.3. More specifically, the gradation value of changing the subpixels was computed from the difference in the RGB values of the two switching colors. Then, the gradation value was converted to the luminance value.

3.2 Experimental results and discussion

3.2.1 Presence or absence of flicker by switching of same luminance colors

Table 4 indicates the number of test subjects who answered, "there is no flicker," and the numbers are hereafter referred to as evaluation points. Table 4 shows that the evaluation points are divided into a case with more than 12 test subjects (boldfaced letters in Table 4 indicate a number of more than 12 test subjects) and cases with less than 6 test subjects. Owing to the division, the combination for which half or more of the test subjects answered, "there is no flicker" comprised 20 sets, and the other combinations comprised 41 sets. Thus, it became clear that a flicker occurred even if two colors of the same luminance value are switched. This result suggests that flicker is caused by another factor other than luminance of two colors.

3.2.2 Range of luminance change in subpixels

The gray columns in Table 4 indicate the combination for which the range of luminance change in three subpixels is contained within the flickerless luminance range clarified in Section 2.3, which form 17 combinations. Of these, 15 sets were in agreement with the combinations where half or more of test subjects answered, "there is no flicker." Therefore, the luminance change in subpixels is considered one of the factors that cause flicker.

Table 4 Number of test subjects assessing "there is no flicker."

Combination Luminance [cd/m ²]	R-G	R-B	R-Y	R-C	R-M	G-B	G-Y	G-C	G-M	B-Y	B-C	B-M	Y-C	Y-M	C-M
10	14	2	1	14	14	0	16	15	16	0	0	0	16	12	14
20	0	—	0	0	12	—	11	15	1	—	—	—	15	0	0
30	0	—	0	0	3	—	4	14	0	—	—	—	12	0	0
40	—	—	—	—	—	—	0	14	0	—	—	—	1	0	0
50	—	—	—	—	—	—	2	13	0	—	—	—	0	0	0
60	—	—	—	—	—	—	0	15	—	—	—	—	3	—	—
70	—	—	—	—	—	—	0	14	—	—	—	—	2	—	—
80	—	—	—	—	—	—	1	12	—	—	—	—	1	—	—
90	—	—	—	—	—	—	0	6	—	—	—	—	1	—	—
100	—	—	—	—	—	—	—	—	—	—	—	—	0	—	—
110	—	—	—	—	—	—	—	—	—	—	—	—	0	—	—

R: Red (n,0,0); G: Green (0,n,0); B: Blue (0,0,n); Y: Yellow (n,n,0); C: Cyan (0,n,n); M: Magenta (n,0,n); n: Gradation value;
Boldfaced letters indicate numbers for more than 12 test subjects; Gray column indicates the combination where the luminance of all subpixels is changed to the flickerless luminance range.

In order to investigate the relation between the luminance change in subpixels and the flicker, we varied the range of luminance change. In particular, we carried out two methods of subsequent changes.

First, the range of luminance change in the blue subpixel in the combination of blue and yellow at 10 cd/m² was narrowed by decreasing the gradation value for the subpixel in steps of 1. The combination was typical in that all test subjects answered, "there is a flicker." Among the three subpixels, only the range of luminance change of blue subpixel exceeded the flickerless luminance range. It ranged from 0.0 to 8.7 cd/m². However, flicker did not occur when the range of luminance change on blue subpixel was changed to the range from 0.0 to 5.4 cd/m². That is, the flicker was lost because the range of luminance change in the subpixels was contained within the flickerless luminance range described in Section 2.3 (upper limit of the flickerless luminance range was 5.5 cd/m² when the luminance value of used color 1 was 0.0 cd/m²).

Next, the ranges of luminance change in the three subpixels in the combination of green and magenta at 10 cd/m² were enlarged separately increasing the gradation value of subpixels in steps of 1. The combination was a typical one in that all test subjects answered, "there is no flicker." The ranges of luminance change on each subpixel were contained within the flickerless luminance range. They ranged from 0.0 to 6.4 cd/m² on the red subpixel, from 0.0 to 10.3 cd/m² on the green subpixel, and from 0.0 to 2.9 cd/m² on the blue subpixel. However, flicker occurred when the range of luminance change on each subpixel was changed to 0.0 to 11.3 cd/m² on the red subpixel, 0.0 to 13.8 cd/m² on the green subpixel, and 0.0 to 5.6 cd/m² for the blue subpixel. The thresholds of flicker are slightly different from the result described in Section 2.3. These differences arise because the flickerless luminance range is decided by half or more of the test subjects, and ambiguity is included in the judgment of the flicker. However, from the above investigation, it is clarified that the luminance change in subpixels influences flicker. Therefore, control of the luminance change on subpixels will enable reduction of flicker.

4 INVESTIGATIONS OF FLICKER BY SWITCHING OF ACHROMATIC COLORS

Since perception of the brightness varies with the type of color,

the perception of the flicker may depend on the type of switching colors. In this section, the presence or absence of flicker is investigated when the achromatic colors are alternately displayed.

4.1 Experimental method

Table 5 shows details of used color 1. There are 13 types of achromatic colors whose luminance levels are incremented in 10 cd/m² steps. Used color 2 includes colors with luminance values different from those of used color 1. The methods for changing the luminance value are similar to the methods described in Section 2.2. Further, the test subjects, the judgment standards, and experimental conditions are the same as those described in Section 2.2. Moreover, the range of luminance change in all the subpixels on the alternating display were compared with the luminance range clarified in Section 2.3.

4.2 Experimental results and discussion

Figure 6 shows the results of the experiment. The flickerless luminance range with switching of achromatic colors is clearly within the range of about ± 4.7 cd/m². No significant differences are confirmed when using two methods for changing the luminance value of used color 2. Therefore, the flickerless luminance range was determined by half or more test subjects, as discussed in Section 2.3.

In addition, the ranges of luminance change in each subpixel for switching of achromatic colors are within the flickerless luminance range given in Section 2.3. Therefore, the luminance change in subpixels is considered one of the factors causing flicker, similar to the results of switching of the same luminance colors (see 3.2.2). This result implies that regardless of whether the color used for display switching has coloration, the occurrence of flicker is dependent on the luminance change in the subpixels. Therefore, flicker could be reduced by using two colors for which the luminance values of subpixels switch within the flickerless luminance range.

5 CONCLUSION

This paper clarified the influence of the luminance change in subpixels on the occurrence of flicker for alternating display of colors on an LCD. The results obtained are as follows:

- (1) Flicker occurs even if two colors of the same luminance value

are switched.

- (2) The occurrence of flicker depends on the extent of the luminance change in subpixels.
- (3) The occurrence of flicker also depends on the luminance change in the subpixels, regardless of whether the color used for display switching has coloration.

In the future, we will conduct investigations using LCDs with various output luminance levels to improve the versatility of the finding in this study.

Table 5 Values of RGB in one of the other colors used for the alternating display of chromatic colors

Luminance [cd/m ²]	Gray	Luminance [cd/m ²]	Gray
10.0	(147, 147, 147)	80.0	(141, 141, 141)
20.0	(168, 168, 168)	90.0	(150, 150, 150)
30.0	(184, 184, 184)	100.0	(158, 158, 158)
40.0	(198, 198, 198)	110.0	(167, 167, 167)
50.0	(110, 110, 110)	120.0	(174, 174, 174)
60.0	(121, 121, 121)	130.0	(182, 182, 182)
70.0	(131, 131, 131)	—	—

Figure 6 Flickerless luminance range of subpixels with achromatic colors

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